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Report 1607

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## RESISTANCE CHARACTERISTICS OF A 70-FOOT HYDROFOIL MISSILE RANGE PATROL BOAT

by



Donald L. Blount

[redacted]

HYDROMECHANICS LABORATORY
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## NOTATION

| | |
|---|---|
| CG | Center of gravity |
| EHP | Effective horsepower |
| $F_\nabla$ | Volume Froude number $(v/\sqrt{g\nabla^{1/3}})$ |
| g | Acceleration due to gravity (ft/sec$^2$) |
| $L_p$ | Chine length parallel to baseline (ft) |
| LCG | Longitudinal center of gravity location |
| LOA | Length overall (ft) |
| R | Resistance (lb) |
| S | Wetted surface (ft$^2$) |
| SW | Salt water |
| V | Speed (knots) |
| v | Speed (ft/sec) |
| WLC | Wetted length of chine (ft) |
| WLK | Wetted length of keel (ft) |
| $\alpha_a$ | Angle of attack of aft foil with respect to baseline (deg) |
| $\alpha_f$ | Angle of attack of forward foil with respect to baseline (deg) |
| $\Delta$ | Displacement at rest, weight of (lb) |
| $\nabla$ | Displacement at rest, volume of (ft$^3$) |
| $\lambda$ | Linear ratio |
| $\tau$ | Model trim angle with respect to baseline (deg) |

## ABSTRACT

Model tests were made at various displacements, center of gravity locations, and foil angles to evaluate two hull-foil combinations. The forward foils were surface-piercing dihedral foils, and the two alternative aft foils were a horizontal submerged foil with two struts and a dihedral submerged foil with a single strut. The struts and foils were of ogive sections. The single-strut aft foil gave the least drag in the takeoff range but the double-strut foil was better in the flying range. It was evident that the forward foil controlled the flying height whereas the aft foil controlled the flying trim.


## INTRODUCTION

The Bureau of Ships designed a Hydrofoil Missile Range Patrol Boat and requested that model tests be conducted to predict and evaluate its performance for various conditions.[1,2] The objectives of this test program were to:

1. Determine the more favorable aft foil configuration of the two proposed.

2. Determine the total resistance of the configuration in the displacement and flying conditions.

The objectives have been met and are reported herein.

## DESCRIPTION OF MODEL

The model, designated Model 4770, was manufactured to a linear ratio of 6.0. The hull was made of wood; the foil assemblies, of aluminum. Drawings of the hull are shown in Figures 1 and 2. The forward foils were surface piercing dihedral foils. The two alternative aft foils were a horizontal submerged foil with two struts and a dihedral submerged foil with a

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[1] References are listed on page 5.

single strut. The struts and foils were of ogive sections with the forward and aft foils having 10 percent and 8 percent thickness ratios, respectively. Details of the struts and foils are presented in Figures 3 through 6. The hull-foil combinations were designated Models 4770-1 and 4770-2, respectively, for the doublt-strut aft foil and the single-strut aft foil. The model foil system with attachments makes up about 18 percent of the design displacement. During most of the test program the model was fitted with single-propeller shaft, struts, and dummy hub. Photographs of the model are given in Figures 7 through 10.

## TEST PROCEDURES

Tests were made at various displacements, center-of-gravity locations, and foil angles. Table 1 lists the conditions of these tests. The model was towed in the shaftline; and resistance, trim, and rise of the center of gravity were measured. No turbulence-stimulation device was used. At speeds where the model was partially supported by the hull, the wetted surface and wetted lengths of the hull were estimated from the trim and CG rise. With these data, corrections were made for the difference in ship and model hull frictional drag coefficients. A roughness allowance ($\Delta C_f$) of zero was assumed for these corrections. The remaining forces were assumed to follow Froude scaling.

## TEST RESULTS AND DISCUSSION

Figure 11 shows the effect of change of static trim for both foil configurations. The primary differences occur in the range of takeoff speeds for the conditions tested, and the zero static trim conditions appears to be the best. The data indicated that the takeoff resistance might be reduced further by trimming the model slightly by the bow. However, this trim condition caused the bow to drop, which precluded any chance of reaching the takeoff speed.

The variations in performance caused by changes in the initial incidence angle of the single-strut aft foil are shown in Figure 12. The differences in drag were negligible at speeds beyond takeoff. It is interesting to note that the effect of changing the initial incidence angle of the submerged aft foil is to change the trim angle of the entire boat (in the flying condition) by very nearly the same amount, but in the opposite direction. This phenomenon is readily explained by the fact that for a particular boat weight and CG location, the aft foil must develop a certain lift. Then, neglecting free-surface effects - which for a submerged foil will not be very large - the angle of attack of the rear foil, for a given speed, must remain relatively constant. Accordingly, if the initial incidence angle of the rear foil is decreased by 1 degree, then at each speed in the flying condition the trim of the boat, as a whole, is <u>increased</u> by nearly the same amount.

Model 4770-2 was tested at four displacements to determine the influence of this variable. Figure 13 shows that the value of the dimensionless drag coefficient $R/\Delta$ increases with increase in displacement in the takeoff range. When the craft is supported by the foils, the values of $R/\Delta$ tend to converge. The slight differences at high speeds are on the order of test accuracy and are not considered to be indicative of significant differences. Time permitted running only one test spot for determining the effect of displacement on the performance of Model 4770-1. This spot is indicated by an X on Figure 14, and shows a decrease in $R/\Delta$ for an increase in displacement. This fact is mentioned only to indicate possible gains for the double-strut foil, but no definite conclusions can be drawn without further verification.

The foil angles for Test 13, shown in Figure 14, produced an unstable flying condition. As the speed was increased beyond takeoff, the model began to oscillate in the vertical plane, with amplitudes increasing with speed. At an $F_\nabla$ of about 3.1 (35 knots full scale), the model trimmed by the bow and abruptly dropped to the hull-borne condition.

Each test reported, except Test 18, was made with the model equipped with appendages for single-screw propulsion. Figure 15 shows the increase in $R/\Delta$ with these appendages, and Figure 16 gives the increase in ehp. It should be borne in mind that this increase is strictly applicable only for the condition shown, since other displacements and static trims give rise to different operating heights and trims. Care must be used if these data are used to make estimates of drag for multiple-screw arrangements since different transverse locations expose the shafting to variations of flow.

One objective of this program was to determine the more favorable aft foil assembly. Figure 16 gives ehp versus speed for the best conditions of the boat with each aft foil assembly. The single-strut foil performs more efficiently in the takeoff range; the double-strut foil performs more efficiently in the flying range.

The test revealed two conditions which would seriously affect the operation of this boat. First, the tips of both aft foil assemblies broke the water surface at high speeds. Second, at some speeds the flying level was so high that it permitted the end of the propeller shaft to be above the water surface. From Figure 17 it is possible to estimate the position of the free-water surface with respect to the hull. This information and the previous comments indicate that the downwash and trough formations behind the front foils create serious disturbances in the region of the aft foil.

In Figure 19 (Appendix), the resistance data from two of the best tests of the present design are compared with data from the two best model tests of a Norwegian design, which is reported on in Reference 3. The Norwegian design has an undivided surface-piercing forward foil carrying 40 percent of the load and a submerged aft foil carrying the remaining 60 percent of the load. Both the Norwegian hull and the Model 4770-1 hull lift above the water surface at about $F_{\nabla} = 2.2$; for the same initial trim $\tau_0$, both designs have about the same $R/\Delta$ at takeoff. At speeds both above and below this transition speed range, however, the Norwegian design is distinctly superior. The advantage in the flying range is attributed to the higher aspect ratios of the foils of the Norwegian boat.

## CONCLUSIONS

The results of these tests indicate that the flying trim of a craft of this type is controlled almost entirely by the aft foil. Since the aft foil is of the submerged type, the trim of the craft must be sufficient for this foil to maintain its lifting capacity with changing speed. The front foils are surface-piercing, and their lifting properties can be varied by both angle and area changes. Since they must also maintain constant lift and their angle of attack is controlled by the aft foil, it follows that the flying height is controlled primarily by the forward foils.

These tests show that careful attention should be given to the relative placement of the forward and aft foils. The downwash effects on the aft foil are partially a result of the lateral spacing of the front foils. Increasing the spacing of the forward foils may relieve the existing situation and improve the flow in the region of the propeller.

To reduce the possibility of the bow diving, as encountered during one test, the dihedral foils might be warped so that either the section angles or the camber increases toward the foil tips. Should a condition of negative trim arise, the submerging sections would then have increasing lift coefficients as well as an increasing area to produce a bow-up moment. If a negative lift coefficient is encountered with the present design, the submerging sections and area only increase the diving force.

The wave-profile photographs (Figure 18) give little indication that the hull deflectors separate the flow from the hull at speeds near takeoff. Because they do not appear to be effective at speeds near takeoff, and because it is believed that they will increase the drag at low speeds, it is considered that these deflectors will detract from rather than improve the performance of this boat.

## REFERENCES

1. Bureau of Ships ltr S82/3(44) Ser 449-35 of 25 Sep 1959.

2. Bureau of Ships ltr 9280/3 F0149901 Ser 449-36 of 14 Oct 1960.

3. Lunde, J.K. and Walderhaug, H.AA., "Three Hundred Tons 50 Knots Hydrofoil Craft," ONR Contract N62558-2596.

TABLE 1

Test Conditions

| Test | Model | $\Delta$ (lb SW) | $\tau_o$ deg | LCG % $L_p$ Fwd. sta. 10 | $\alpha_f$ deg | $\alpha_a$ deg |
|---|---|---|---|---|---|---|
| 1,1A | 4770-1 | 90,000 | 0 | 44.1 | 1 | 1 |
| 4,4A | 4770-1 | 90,000 | 1/2 x stern | 42.3 | 1 | 1 |
| 6 | 4770-1 | 100,000 | 0 | 44.2 | 1/2 | 1/2 |
| 7 | 4770-1 | 90,000 | 0 | 44.1 | 1/2 | 1/2 |
| 8 | 4770-2 | 90,000 | 0 | 44.1 | 1 | 1 |
| 9 | 4770-2 | 90,000 | 1/2 x stern | 42.3 | 1 | 1 |
| 10 | 4770-2 | 100,000 | 0 | 44.2 | 1 | 1 |
| 11 | 4770-2 | 110,000 | 0 | 44.2 | 1 | 1 |
| 12 | 4770-2 | 73,415 | 0 | 44.0 | 1 | 1 |
| 13 | 4770-1 | 90,000 | 0 | 44.1 | 0 | 1 |
| 14 | 4770-2 | 90,000 | 0 | 44.1 | 1 | 0 |
| 15 | 4770-2 | 90,000 | 1/2 x stern | 42.3 | 1 | 0 |
| 16 | 4770-2 | 90,000 | 0 | 44.1 | 1 | -1 |
| 17* | 4770-2 | 90,000 | 0 | 44.1 | 1 | -1 |
| 18* | 4770-2 | 90,000 | 0 | 44.1 | 1 | 1 |

* These tests were conducted without propeller shaft and struts.

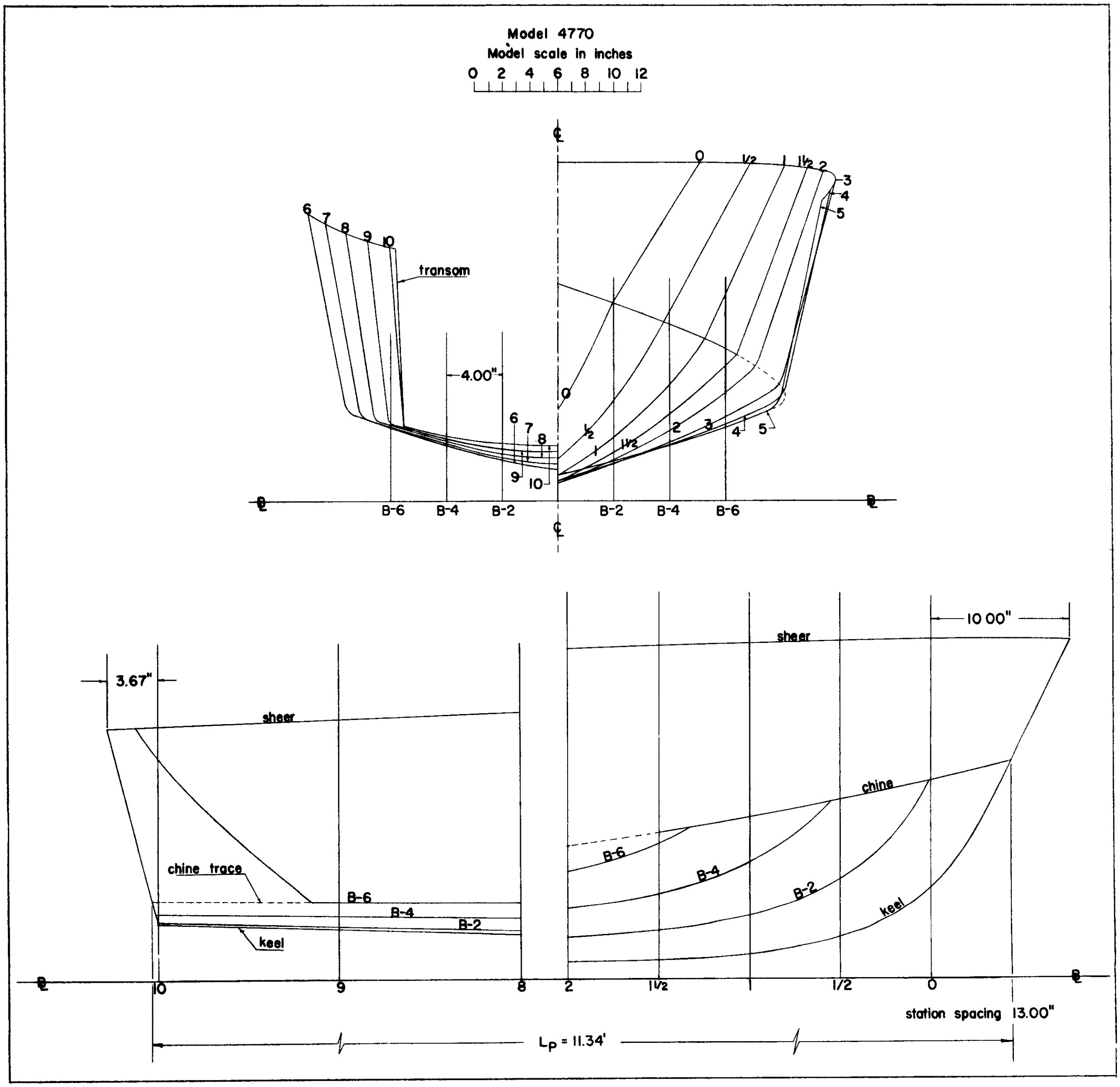



Figure 1 - Model Lines without Hull Deflectors

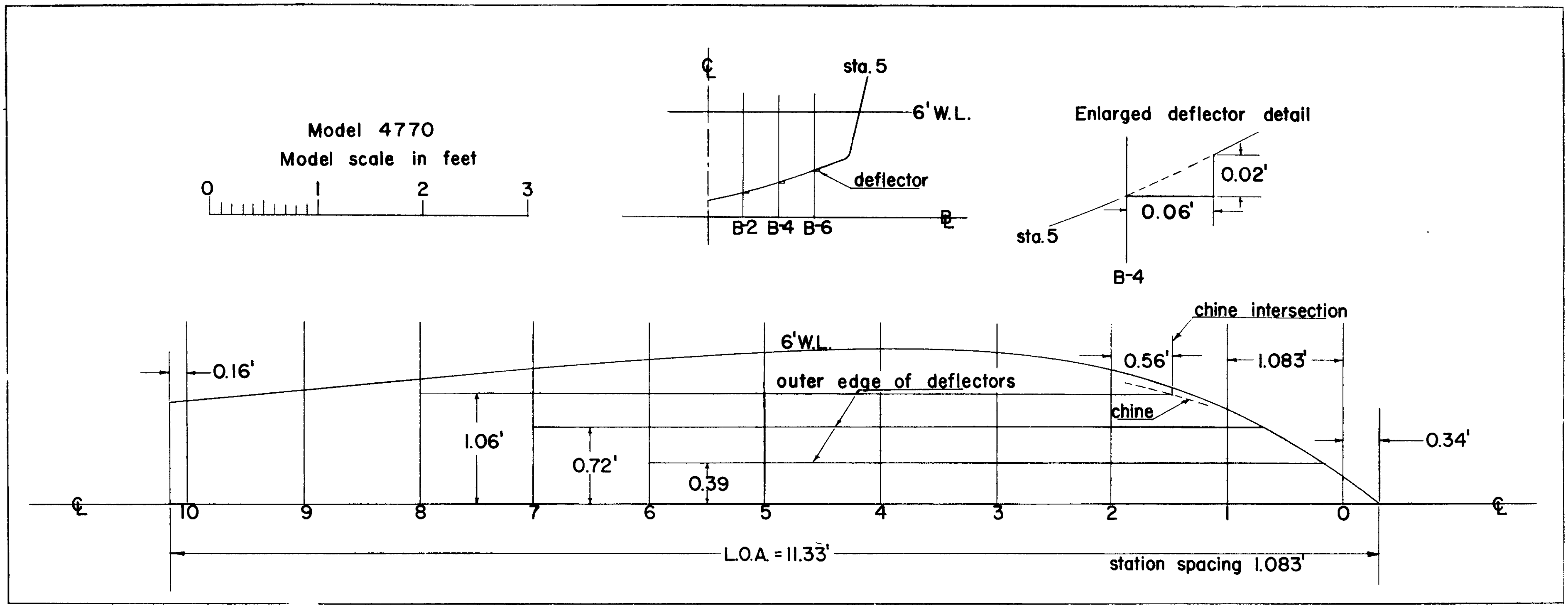



Figure 2 - Hull Deflector Details

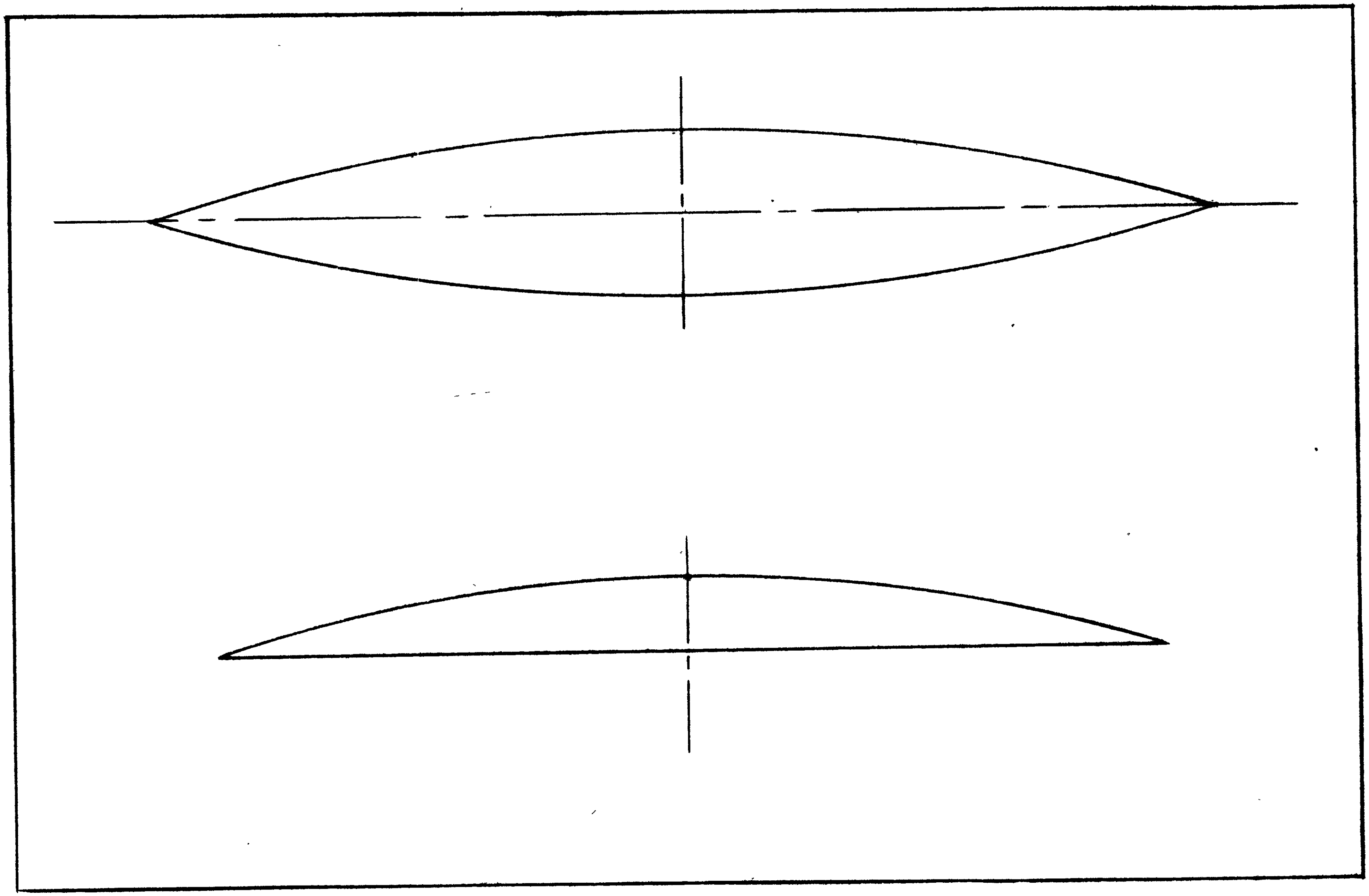


Figure 3 - Typical Foil and Strut Sections

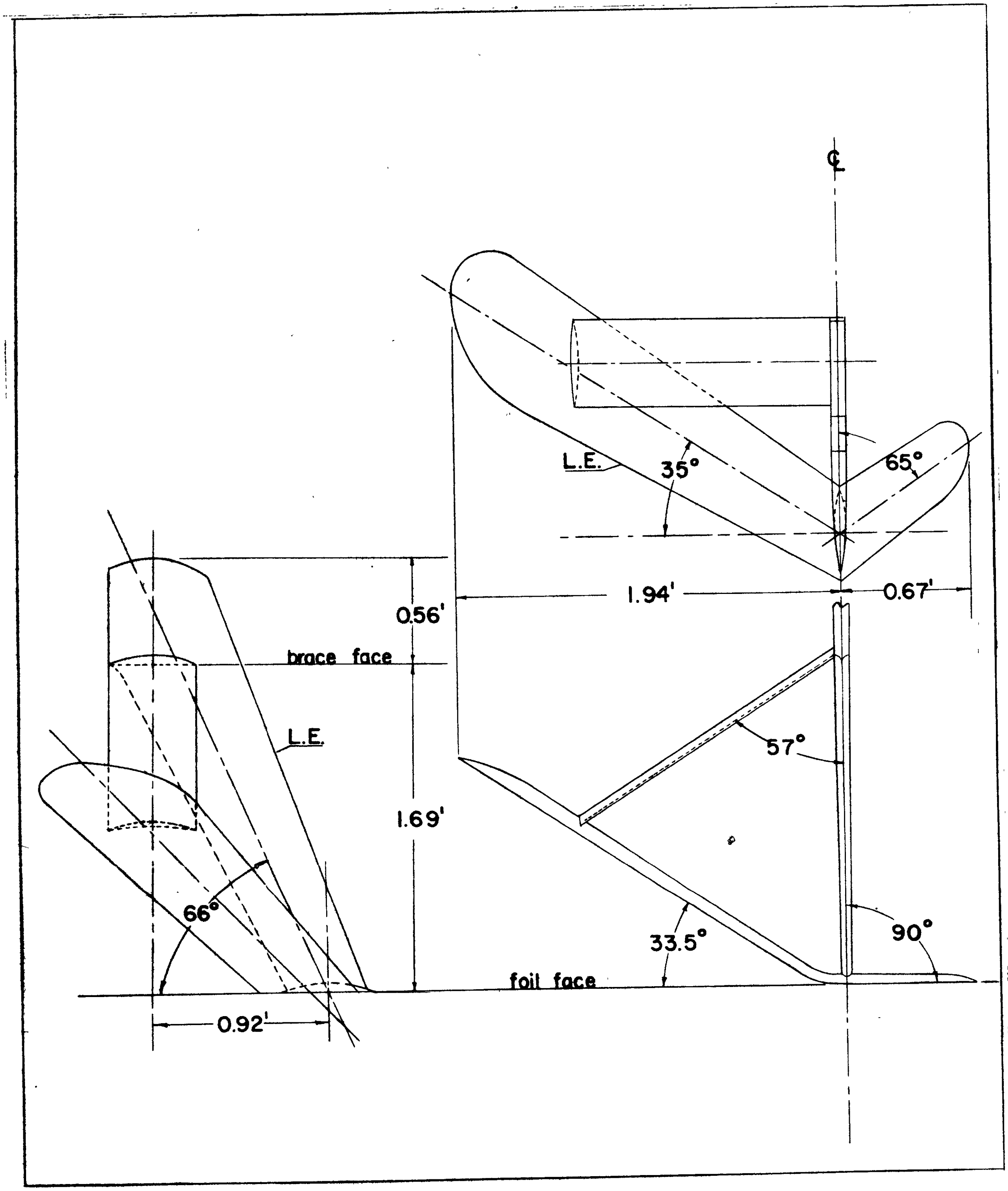



**Figure 4 - Forward Foil Assembly**

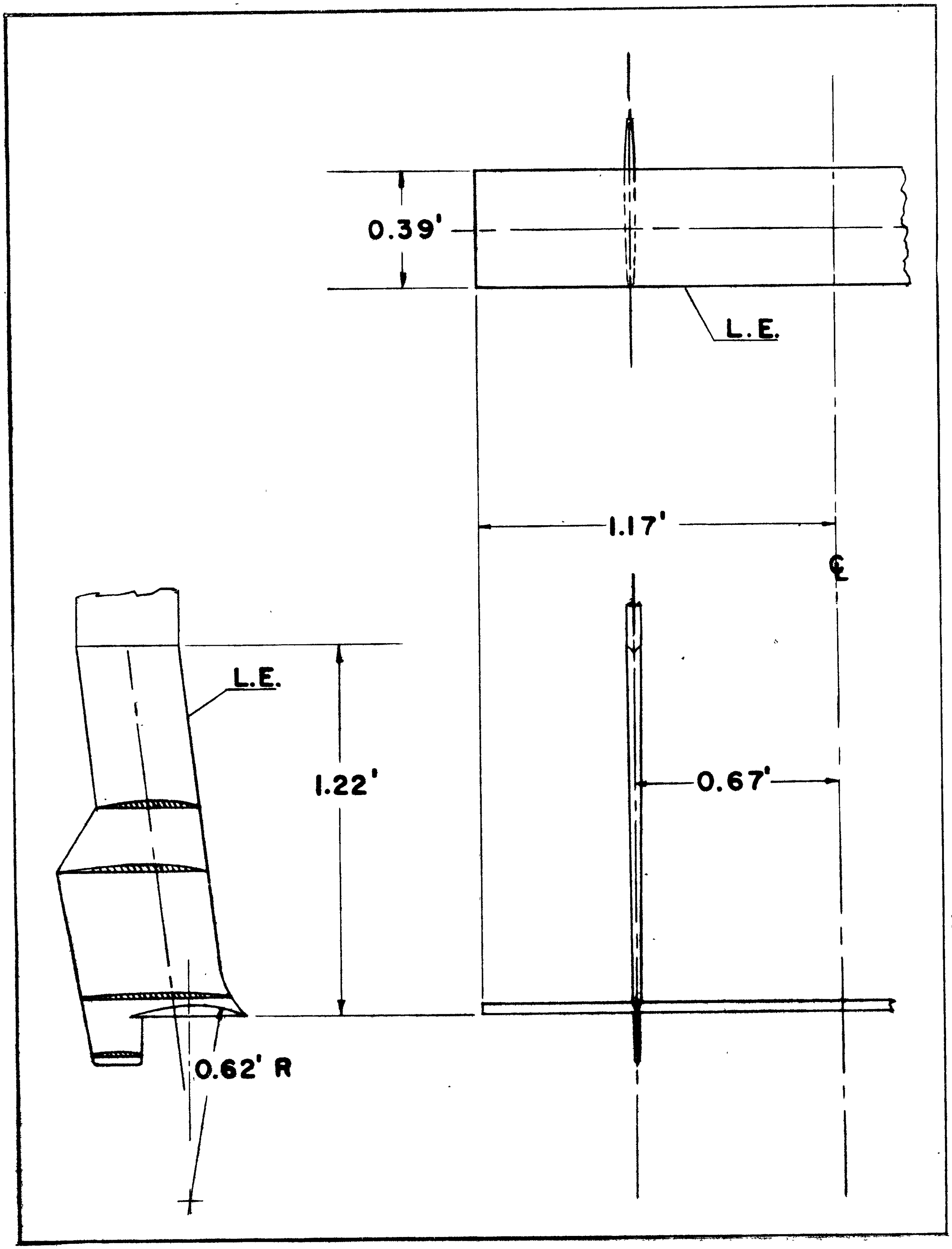



Figure 5 - Double-Strut Aft Foil Assembly

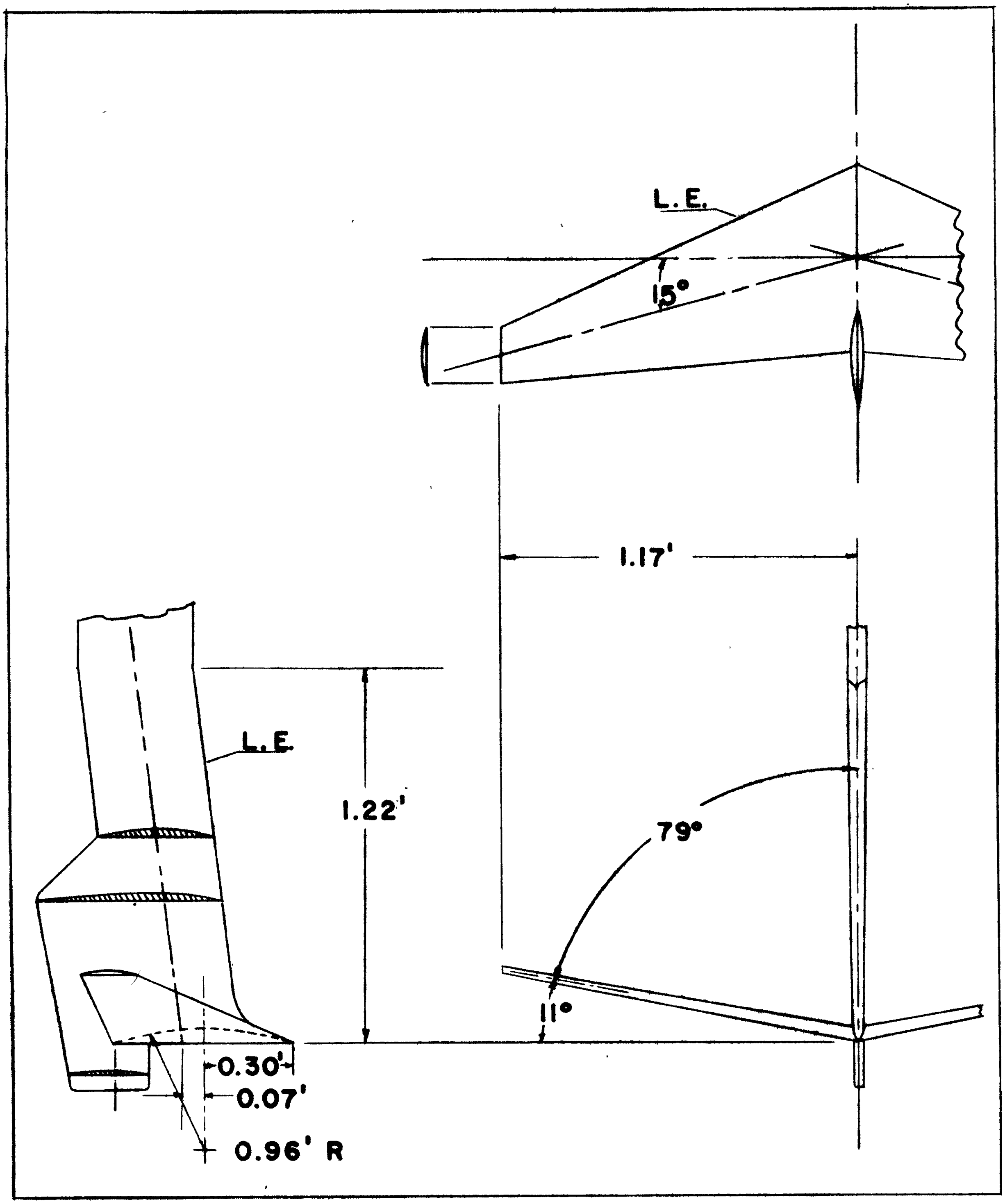



Figure 6 - Single-Strut Aft Foil Assembly


Figure 7 - Model Profile

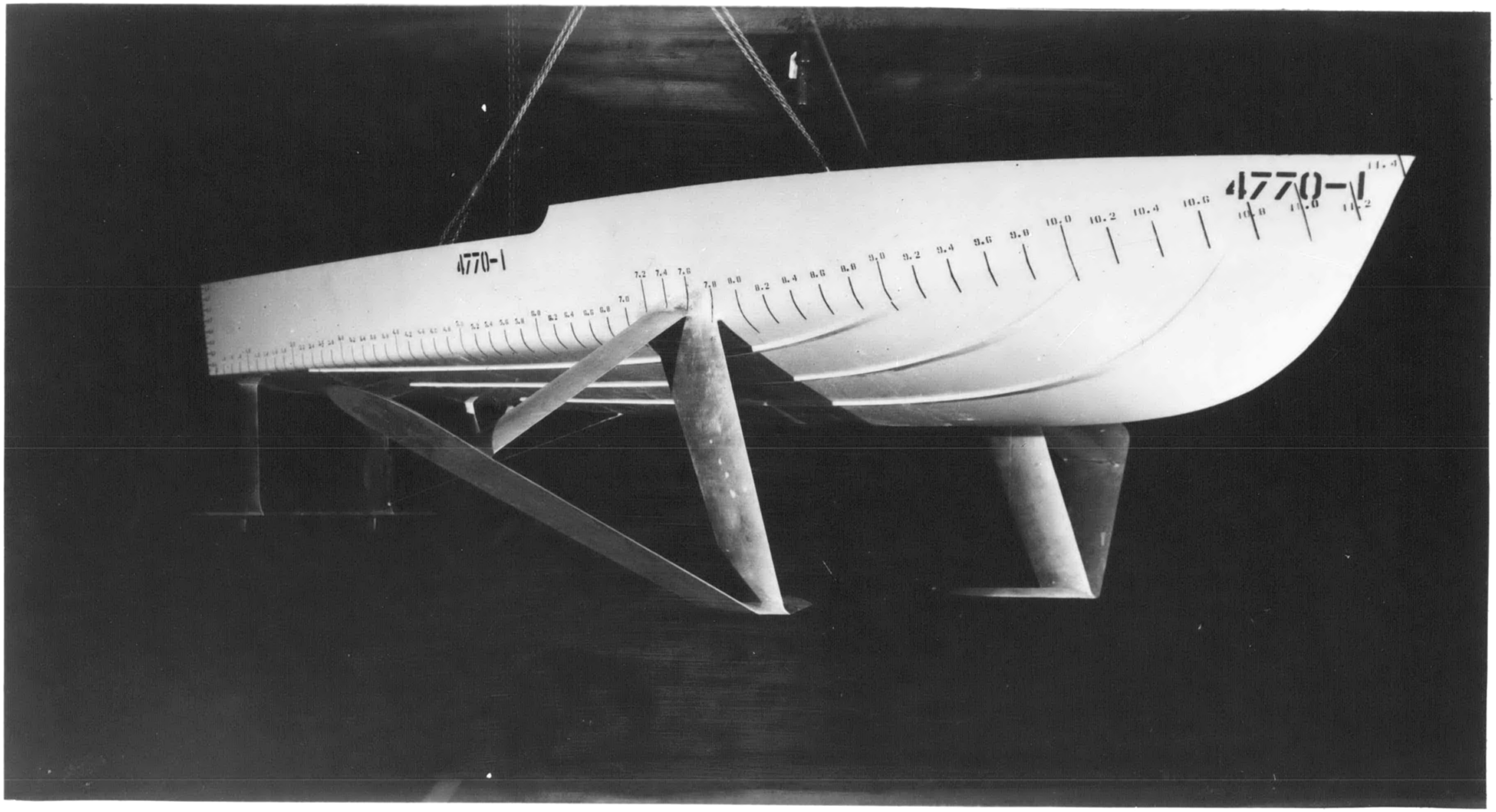



Figure 8 - Bow Quarter View

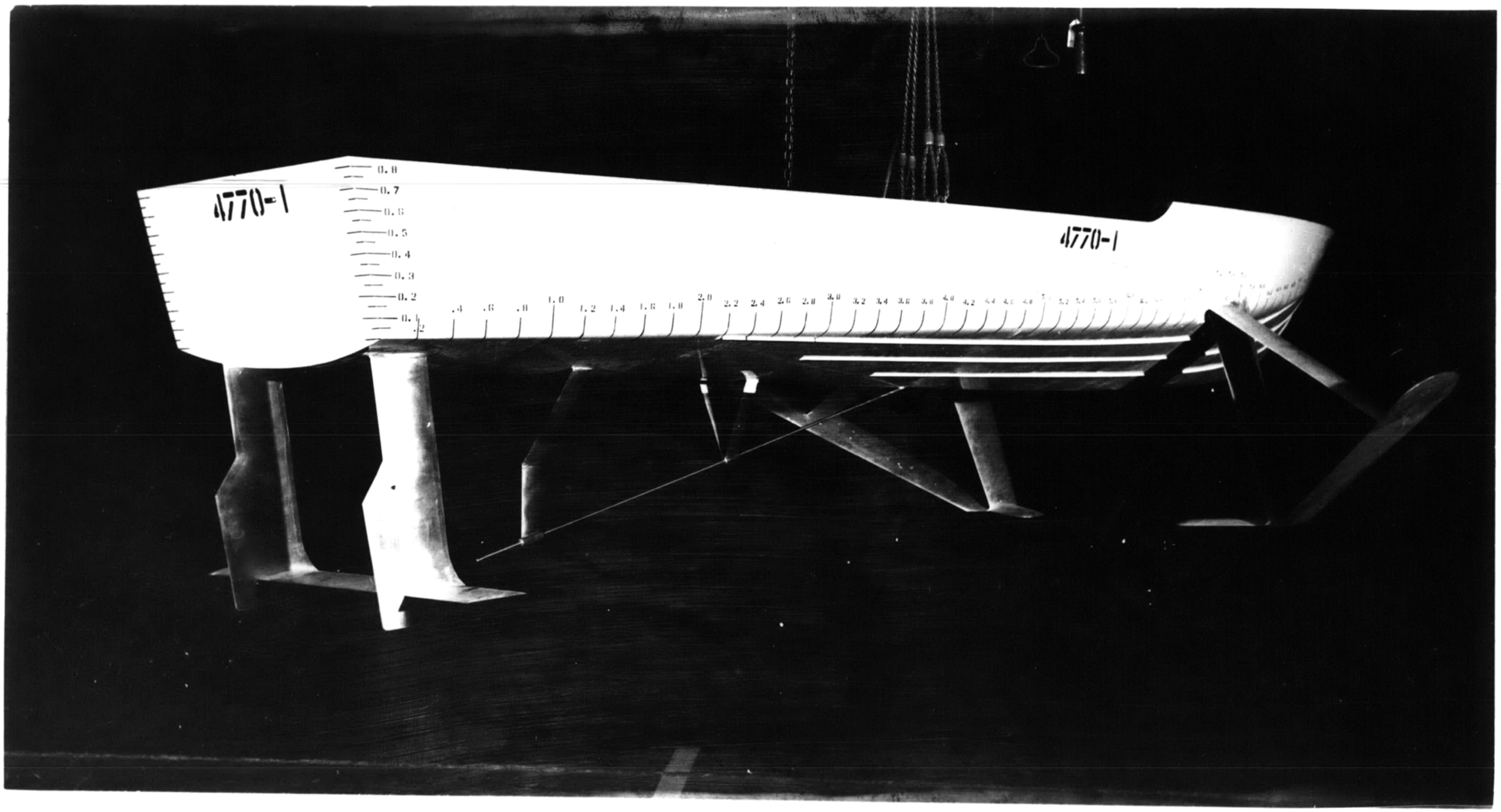



Figure 9 - Stern Quarter View

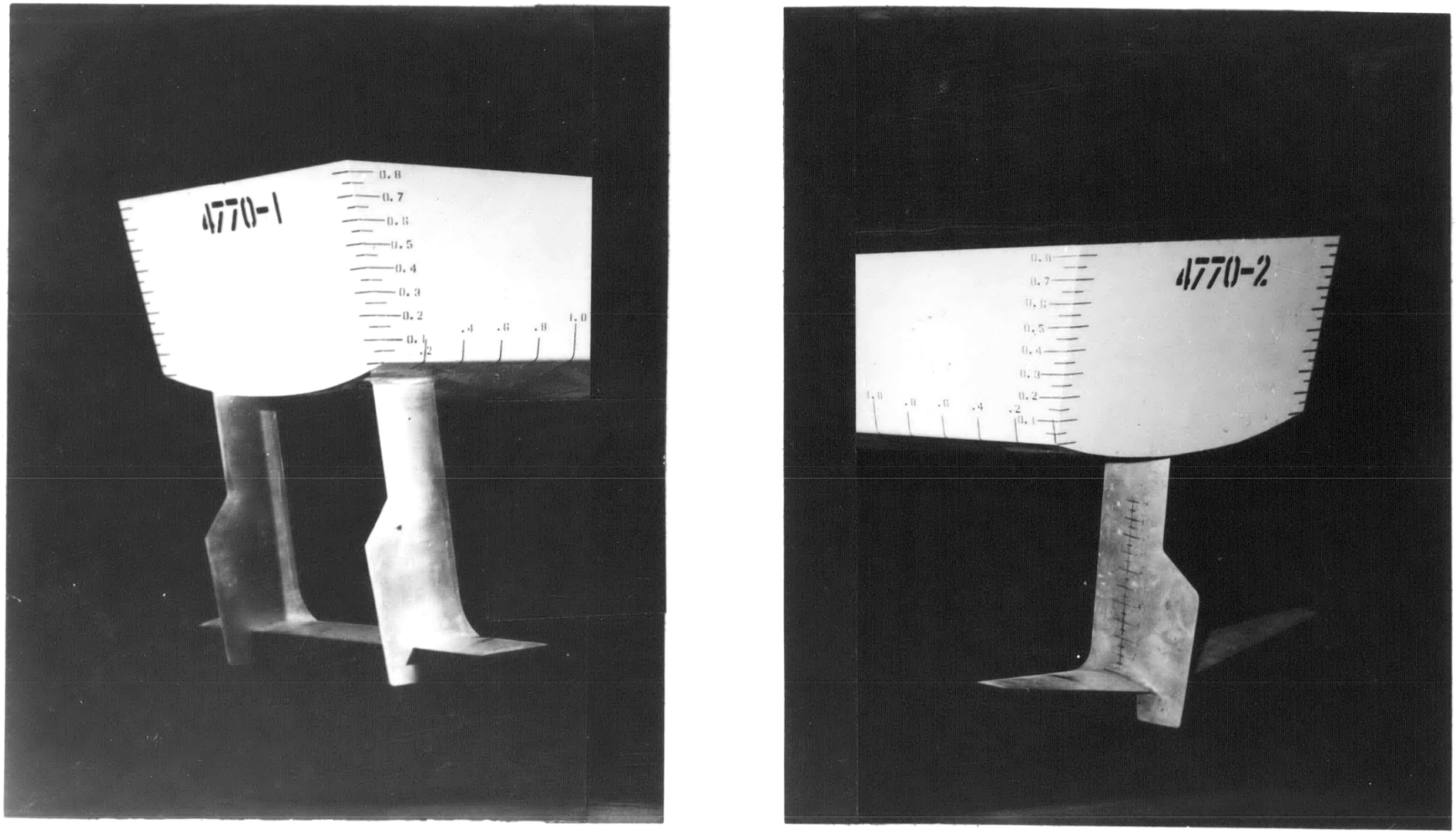



Figure 10 - Stern Foils

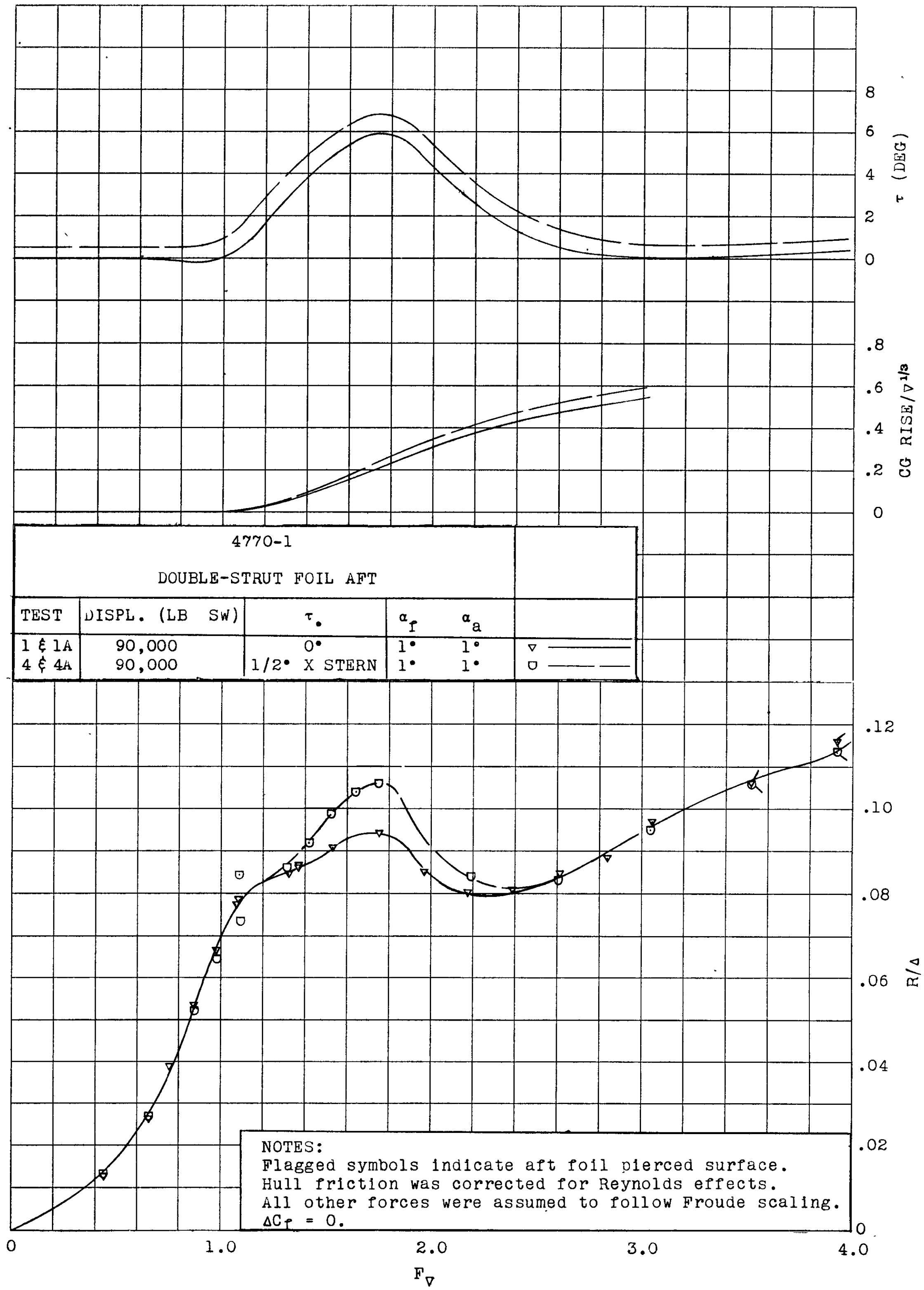



**Figure 11a - Model 4770-1**
**Effects of Variation of Static Trim**

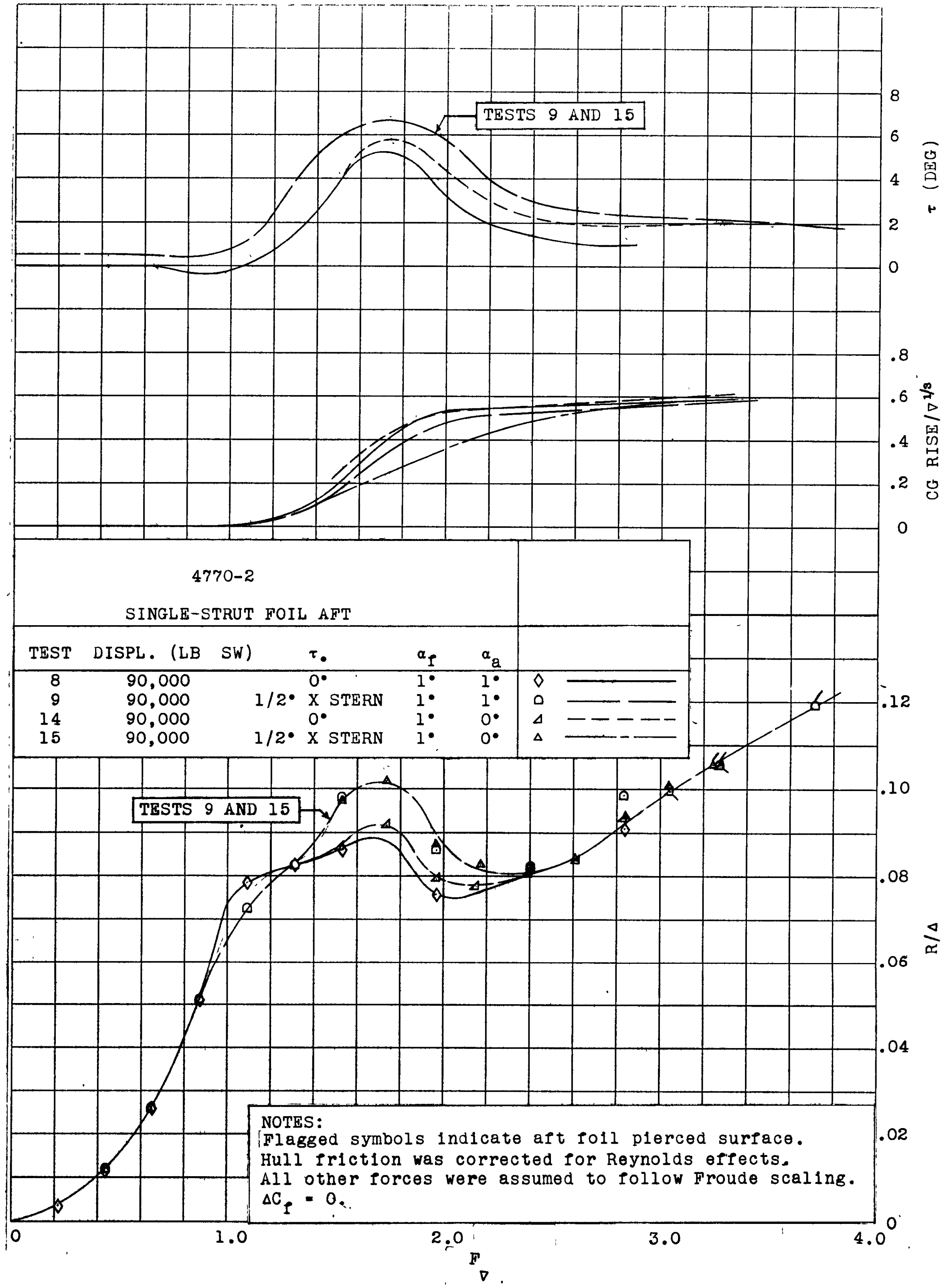



Figure 11b - Model 4770-2

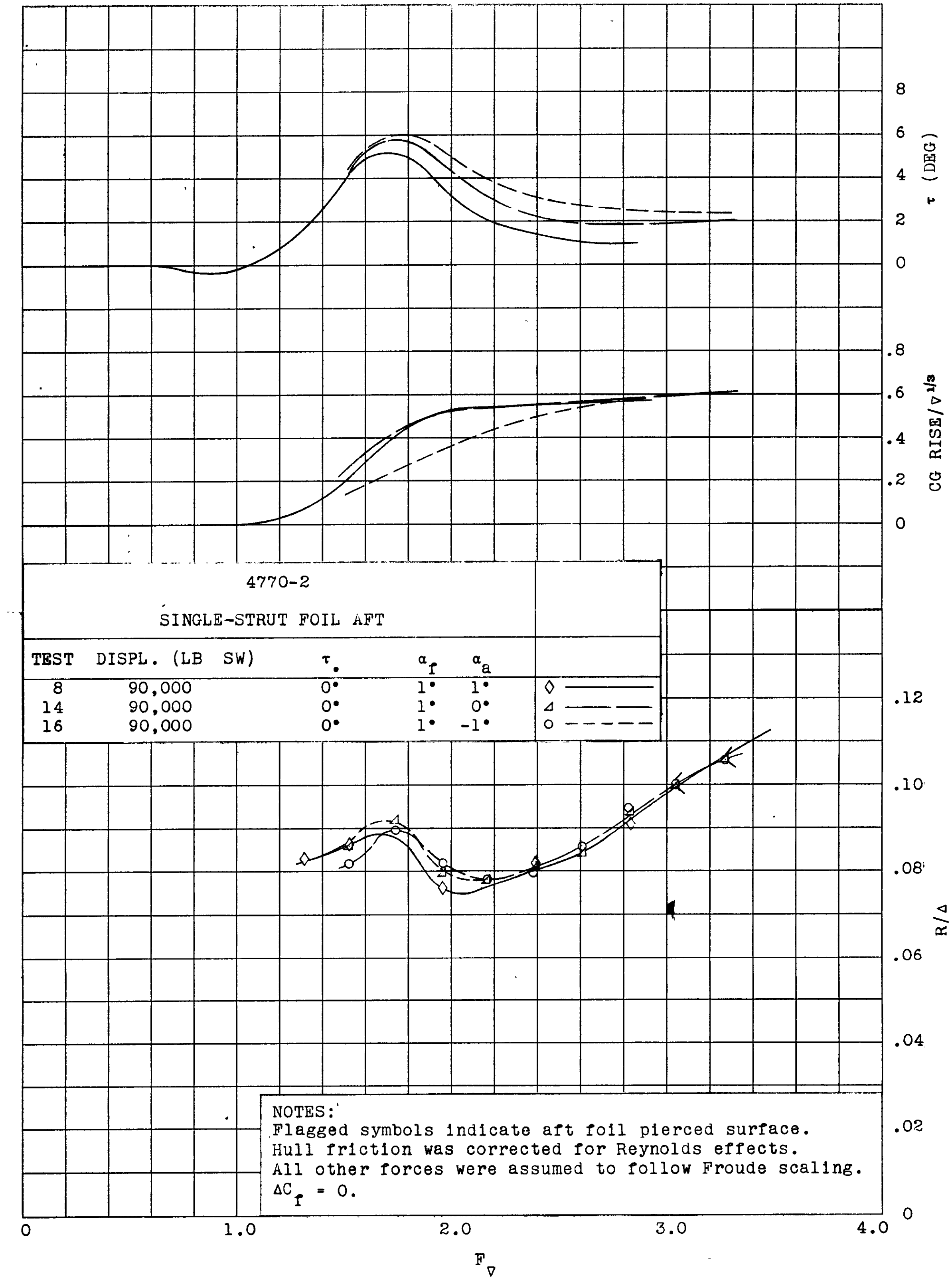



Figure 12 - Effects of Variation of Aft Foil Angle

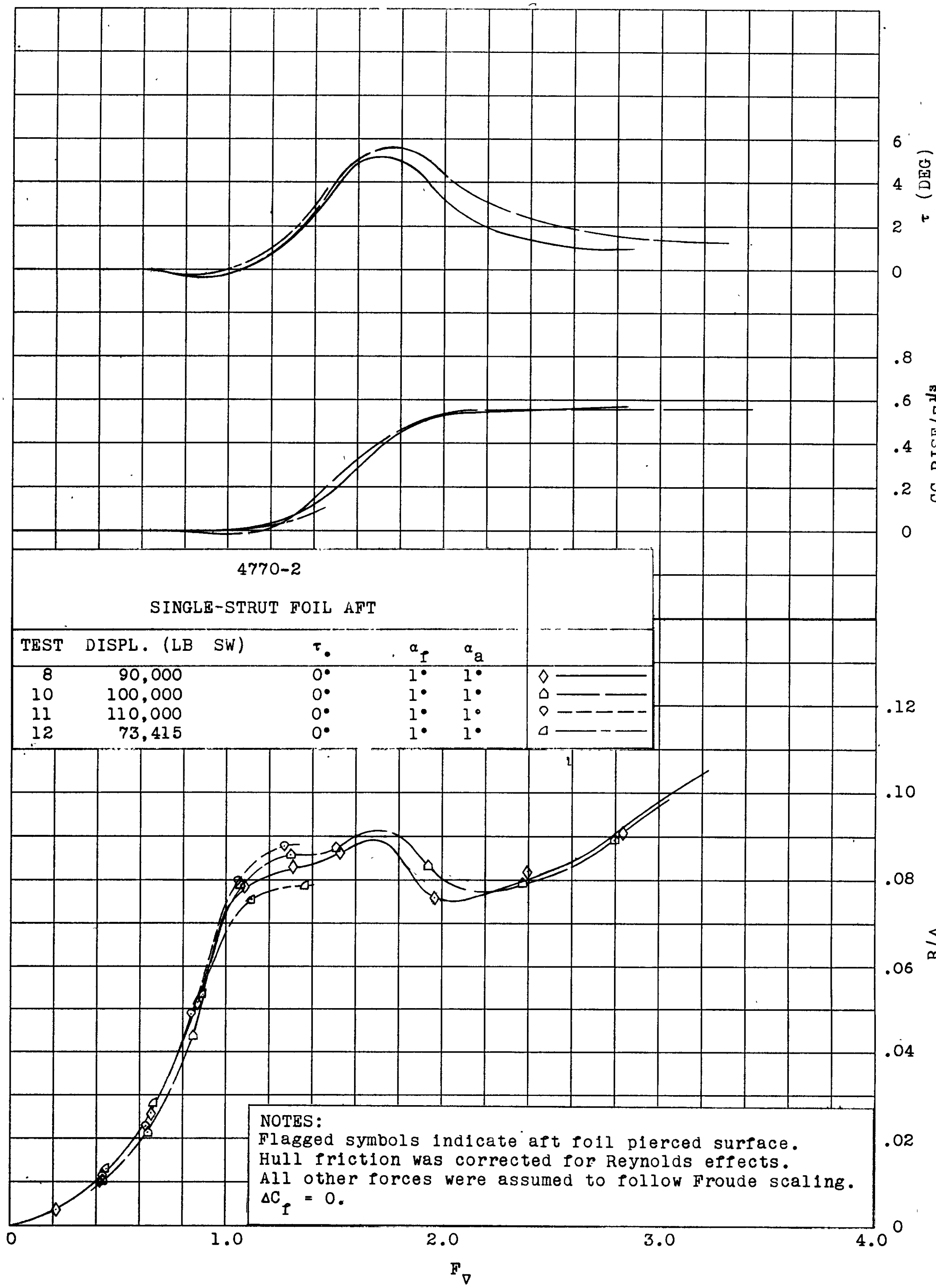



Figure 13 - Effects of Variation of Displacement

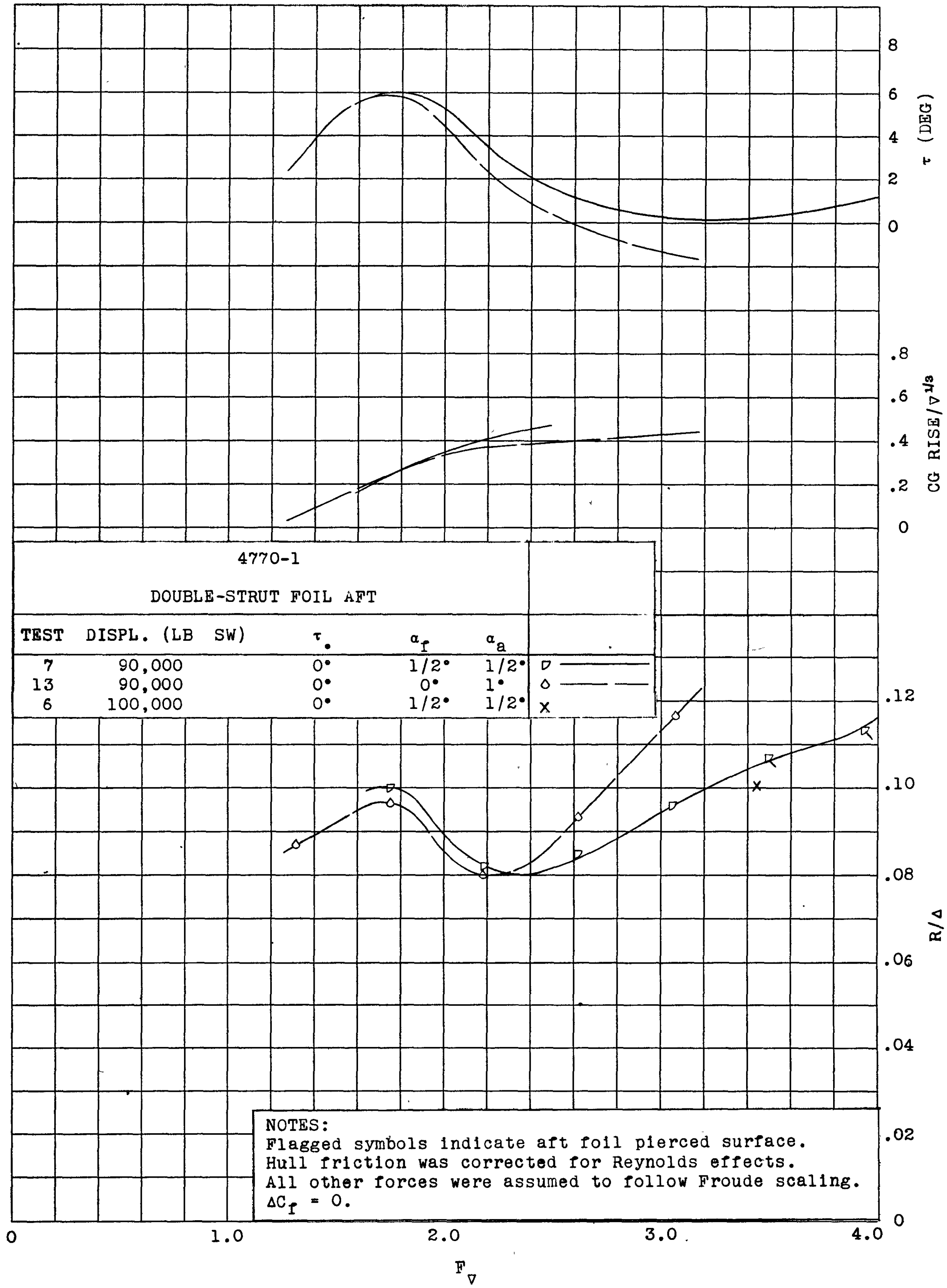



Figure 14 - Effects of Variation of Displacement and Foil Angle

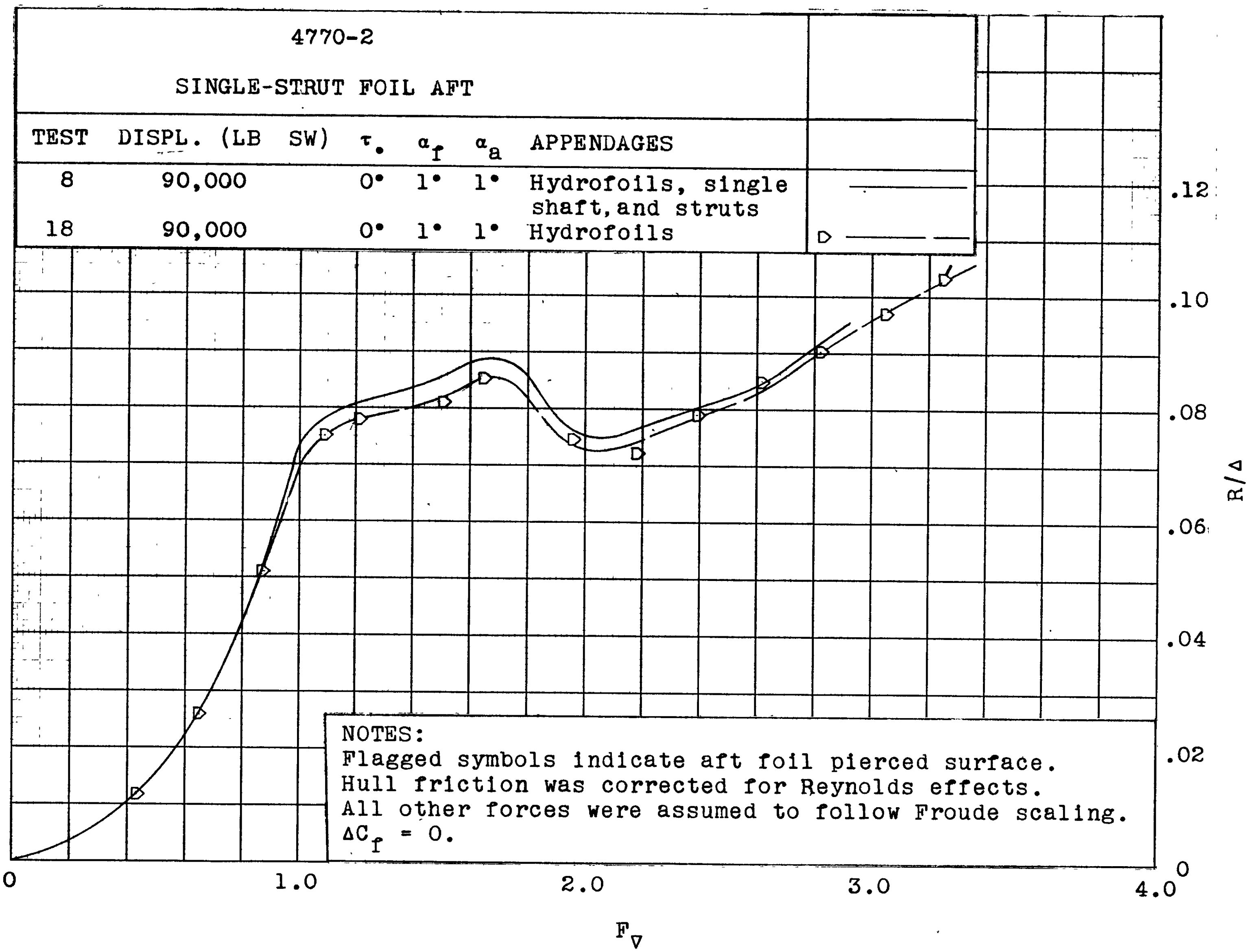



Figure 15 - Effects of Addition of Shaft and Struts

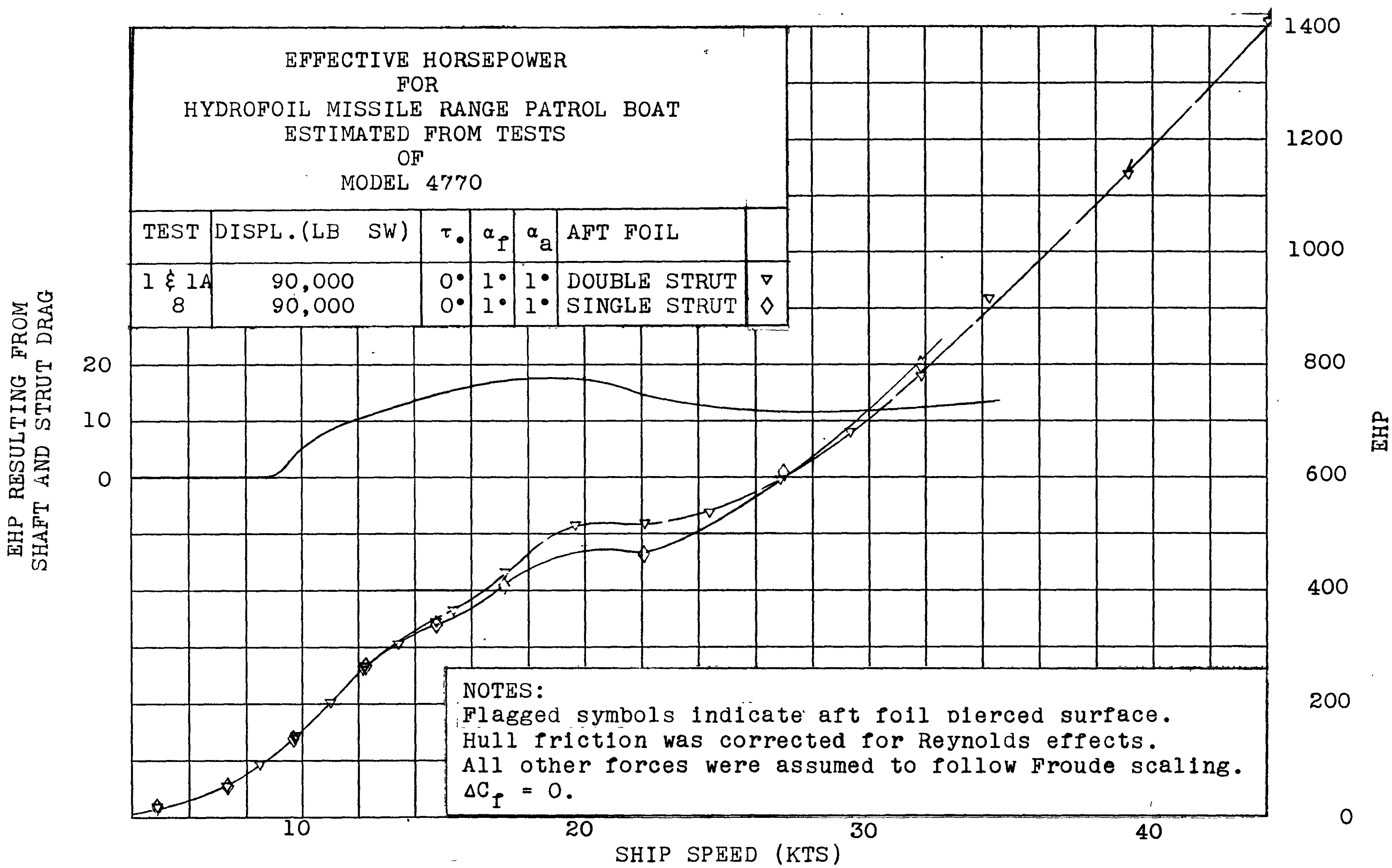



**Figure 16 - Effective Horsepower for Best Conditions of Each Foil Assembly**

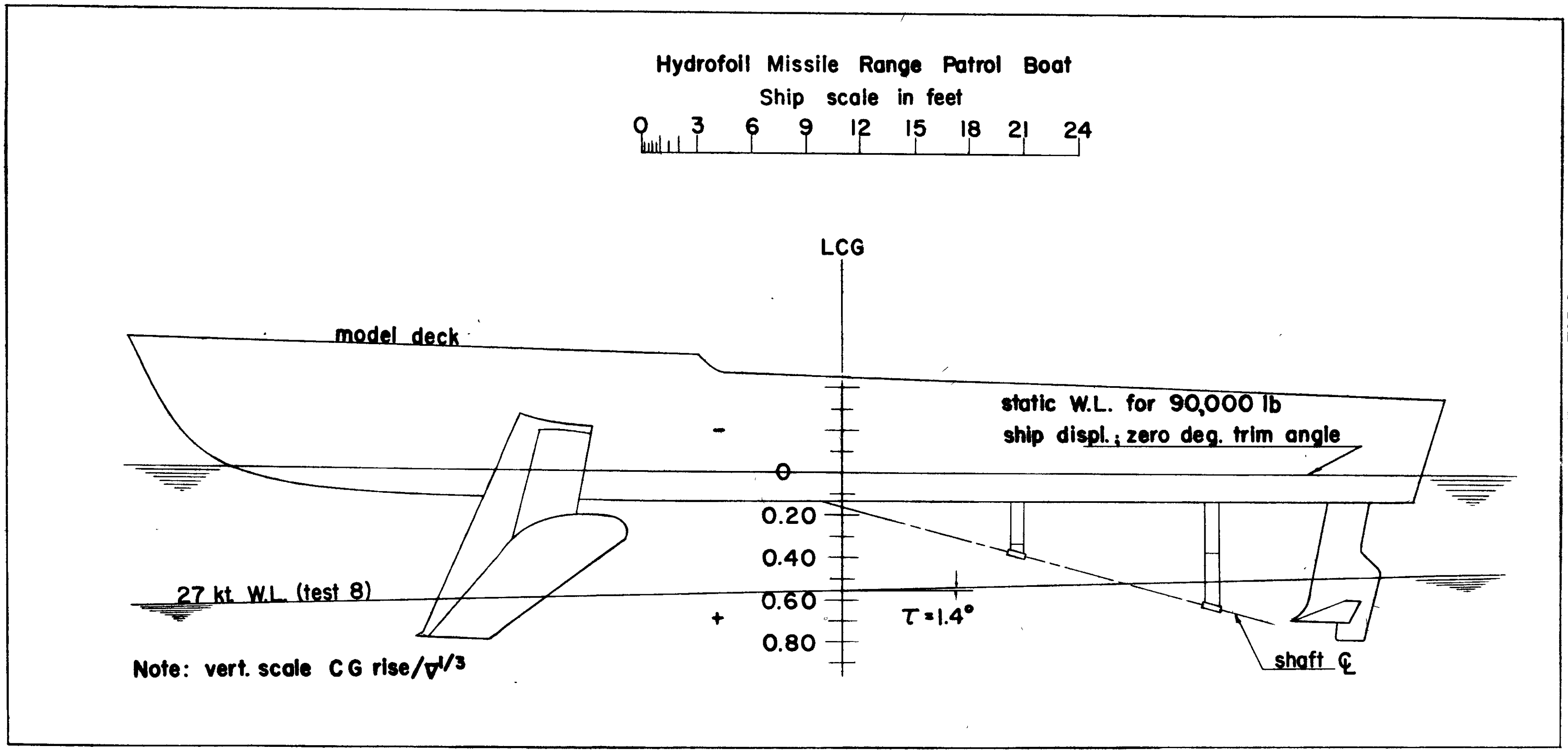
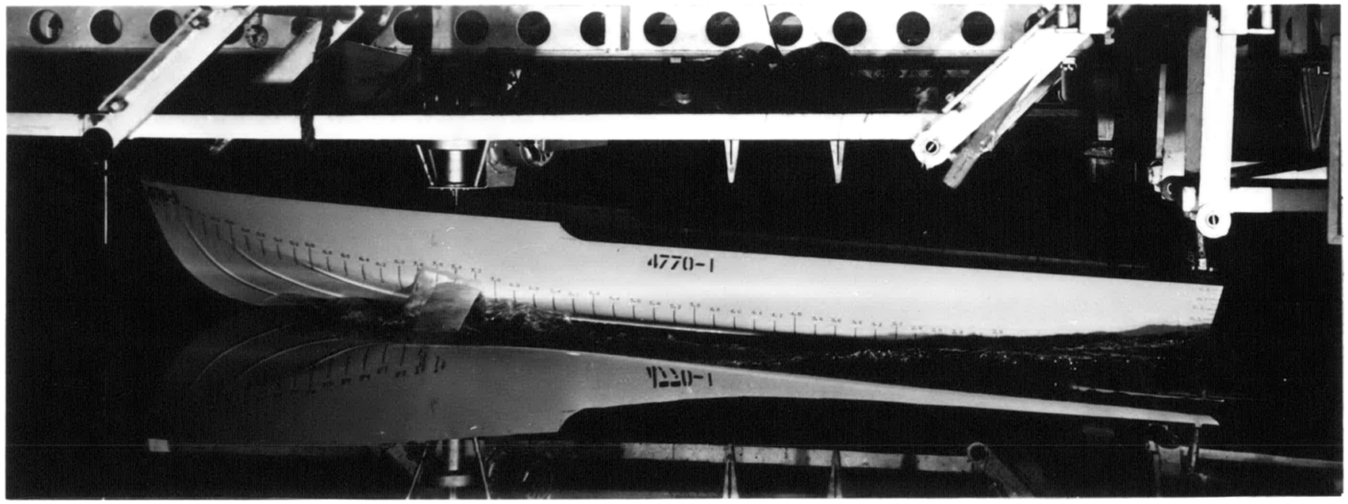
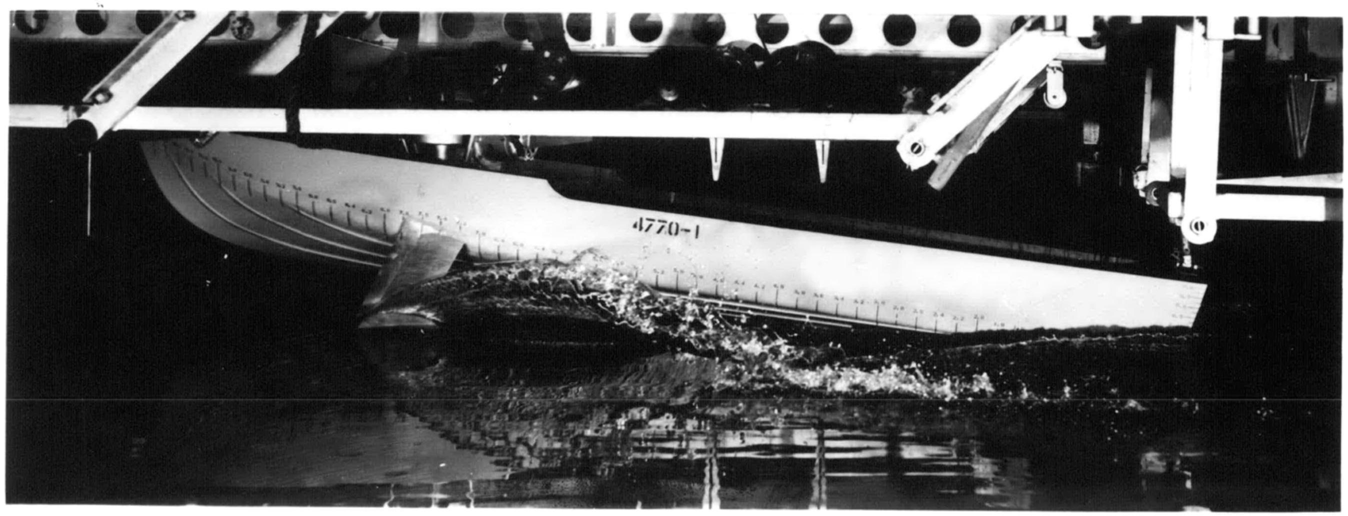



Figure 17 - Information for Determining Approximate Free Water Surface at Various Speeds for 90,000-Pound Ship Displacement at Zero Static Trim

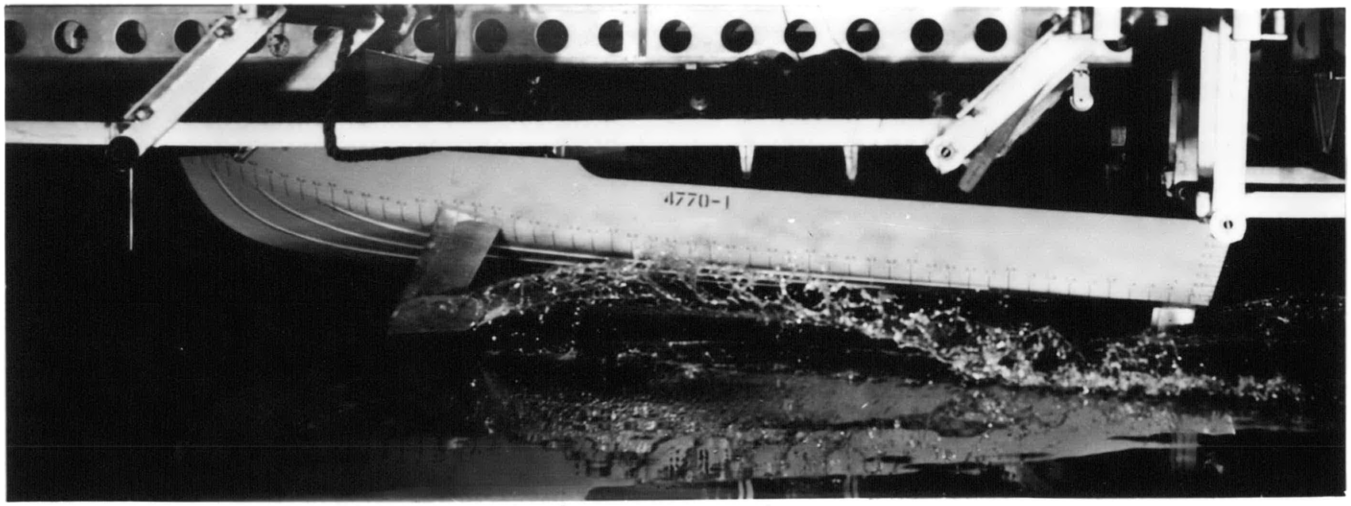



Speed 14.7 knots




Speed 19.6 knots

Figure 18a - Wave Profiles




Speed 24.5 knots


Speed 29.4 knots

Figure 18b - Wave Profiles

## APPENDIX

The data given in Table 2 were taken from Reference 3 and expanded to a full-scale displacement of 100,000 lb SW for comparison in Figure 19. The following important assumptions were necessary for data expansion: (1) The test temperature was $70^{\circ}$F. and (2) the model towpoint was in the thrust line. Deviation from either of these assumptions could produce significant errors in the results shown in Figure 19.

TABLE 2

Model Test Data from Reference 3*

Displacement - 47.35 lb LOA - 6.65 ft

| Test | V kts | R lb | WLK** ft | WLC** ft | S** $ft^2$ | $\tau$ deg | C.G.Rise in | $F_\nabla$ |
|---|---|---|---|---|---|---|---|---|
| **Figure 23** | 0 | 0 | | | | 0.50 | | |
| **I WL** | 1.94 | 1.10 | 5.36 | 6.29 | 9.25 | 0.60 | -0.079 | 0.61 |
| | 2.72 | 2.20 | 5.33 | 6.29 | 9.41 | 0.80 | -0.118 | 0.85 |
| | 3.50 | 3.64 | 5.33 | 6.31 | 9.46 | 1.40 | -0.157 | 1.09 |
| | 4.28 | 4.59 | 4.99 | 6.20 | 9.28 | 2.10 | -0.079 | 1.33 |
| | 5.05 | 4.96 | 3.86 | 3.40 | 5.64 | 3.00 | 0.315 | 1.58 |
| | 5.83 | 5.22 | 0.29 | —— | 0.47 | 3.80 | 1.181 | 1.82 |
| | 6.61 | 4.59 | | | | 3.80 | 1.890 | 2.06 |
| | 7.39 | 3.64 | | | | 2.60 | 2.598 | 2.30 |
| | 8.16 | 3.48 | | | | 1.30 | 3.228 | 2.55 |
| | 8.94 | 3.44 | | | | 0.75 | 3.661 | 2.79 |
| | 9.72 | 3.44 | | | | 0.50 | 4.173 | 3.03 |
| | 10.50 | 3.48 | | | | 0.40 | 4.567 | 3.27 |
| | 11.27 | 3.68 | | | | 0.50 | 4.724 | 3.51 |
| **Figure 24** | 0 | 0 | | | | 0.50 | | |
| **I WL** | 1.94 | 1.12 | 5.28 | 6.29 | 9.31 | 0.60 | -0.079 | 0.61 |
| | 2.72 | 2.27 | 5.29 | 6.31 | 9.48 | 0.80 | -0.157 | 0.85 |
| | 3.50 | 3.64 | 5.32 | 6.31 | 9.64 | 1.40 | -0.197 | 1.09 |
| | 4.28 | 4.52 | 4.95 | 6.16 | 9.25 | 2.10 | -0.079 | 1.33 |
| | 5.05 | 5.01 | 3.88 | 3.94 | 6.27 | 3.00 | 0.236 | 1.58 |
| | 5.83 | 5.53 | 1.51 | 0.77 | 1.68 | 3.80 | 0.866 | 1.82 |
| | 6.61 | 5.29 | | | | 3.80 | 1.732 | 2.06 |
| | 7.39 | 3.79 | | | | 2.60 | 2.677 | 2.30 |
| | 8.16 | 3.42 | | | | 1.30 | 3.386 | 2.55 |
| | 8.94 | 3.42 | | | | 0.75 | 3.858 | 2.79 |
| | 9.72 | 3.55 | | | | 0.50 | 4.252 | 3.03 |
| | 10.50 | 3.68 | | | | 0.40 | 4.488 | 3.27 |
| | 11.27 | 3.68 | | | | 0.50 | 4.724 | 3.51 |

* Neither model towpoint nor test temperature was given.

** Wetted surface and lengths were computed from trim and CG rise.

| DATA SOURCE | TEST | DISPL. (LB SW) | $\tau_o$ | FWD FOIL | $\alpha_f$ | $\alpha_a$ | SYMBOLS |
|---|---|---|---|---|---|---|---|
| REF. 3 | FIG. 23 I WL | 100,000 | 1/2° X STERN | 1 | 1.5° | 1.5° | — —— |
| | FIG. 24 I WL | 100,000 | 1/2° X STERN | 2 | 1.5° | 1.5° | ............ |
| MODEL 4770-1 | 1 & 1A | 100,000 | 0° | | 1.0° | 1.0° | ———— |
| | 4 & 4A | 100,000 | 1/2° X STERN | | 1.0° | 1.0° | -------- |

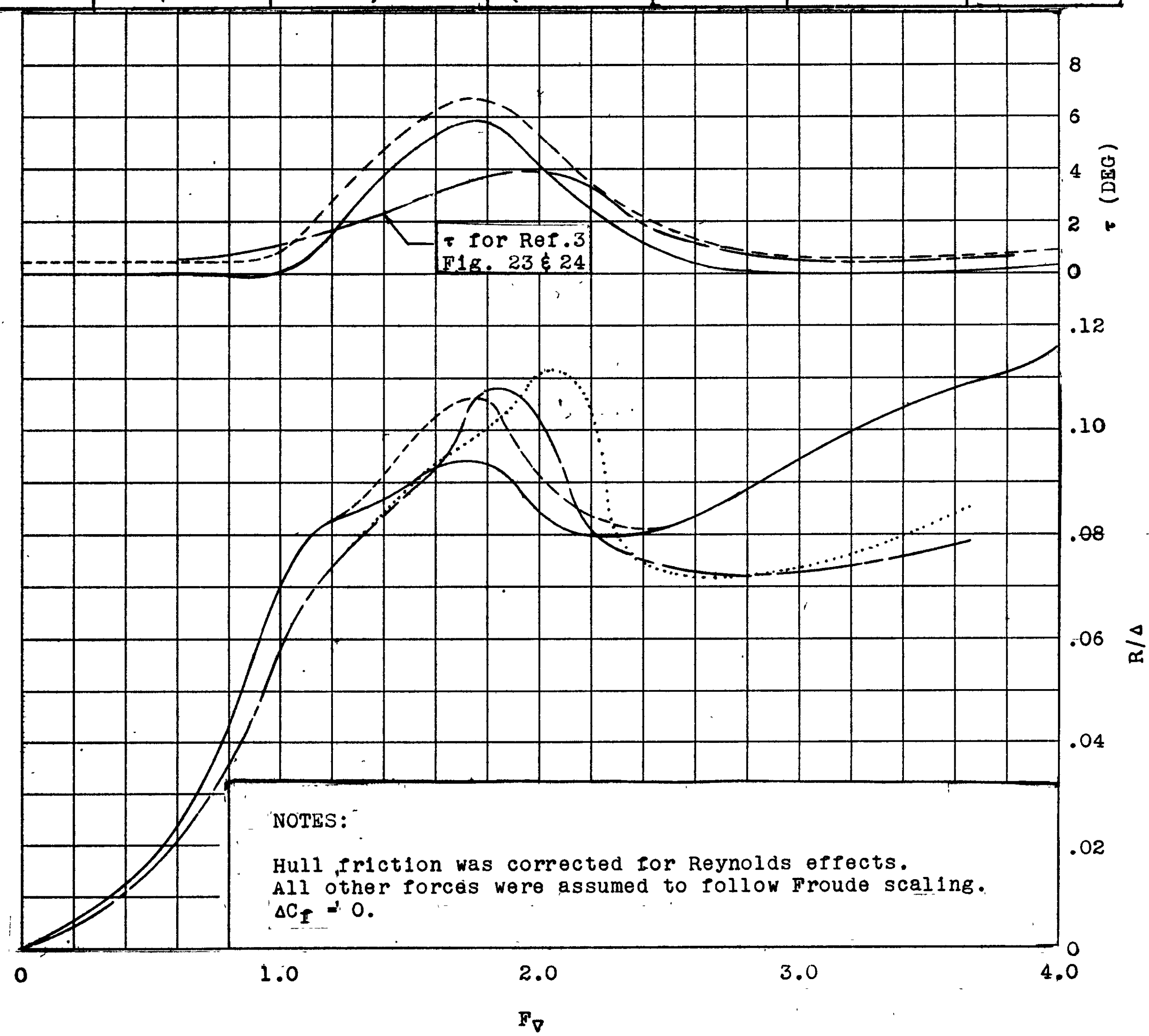



**Figure 19 - Comparison of Data from Model 4770-1 with Data from Reference 3**

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